Conant, Richard T. and Paustian, Keith (2002) ***Potential soil carbon sequestration in overgrazed grassland ecosystems.*** Global Biogeochemical Cycles, 16(4). 90-1---90-9.

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 16, NO. 4, 1143, doi:10.1029/2001GB001661, 2002

Potential soil carbon sequestration in overgrazed grassland ecosystems

Richard T. Conant and Keith Paustian

Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA

Received 19 September 2001; revised 26 March 2002; accepted 20 September 2002; published 31 December 2002.

[1] Excessive grazing pressure is detrimental to plant productivity and may lead to declines in soil organic matter. Soil organic matter is an important source of plant nutrients and can enhance soil aggregation, limit soil erosion, and can also increase cation exchange and water holding capacities, and is, therefore, a key regulator of grassland ecosystem processes. Changes in grassland management which reverse the process of declining productivity can potentially lead to increased soil C. Thus, rehabilitation of areas degraded by overgrazing can potentially sequester atmospheric C. We compiled data from the literature to evaluate the influence of grazing intensity on soil C. Based on data contained within these studies, we ascertained a positive linear relationship between potential C sequestration and mean annual precipitation which we extrapolated to estimate global C sequestration potential with rehabilitation of overgrazed grassland. The GLASOD and IGBP DISCover data sets were integrated to generate a map of overgrazed grassland area for each of four severity classes on each continent. Our regression model predicted losses of soil C with decreased grazing intensity in drier areas (precipitation less than 333 mm yr^{-1}), but substantial sequestration in wetter areas. Most (93%) C sequestration potential occurred in areas with MAP less than 1800 mm. Universal rehabilitation of overgrazed grasslands can sequester approximately 45 Tg C yr^{-1}, most of which can be achieved simply by cessation of overgrazing and implementation of moderate grazing intensity. Institutional level investments by governments may be required to sequester additional C. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 4806 Oceanography: Biological and Chemical: Carbon cycling; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; *KEYWORDS:* soil carbon, grassland/pasture/rangeland management, carbon sequestration, overgrazing, soil degradation

Citation: Conant, R., and K. Paustian, Potential soil carbon sequestration in overgrazed grassland ecosystems, *Global Biogeochem. Cycles*, *16*(4), 1143, doi:10.1029/2001GB001661, 2002.

1. Introduction

[2] Compensatory plant growth in response to grazing has been observed in some plant species and communities under certain conditions [e.g., *McNaughton*, 1979; *Georgaidis et al.*, 1989; *Dyer et al.*, 1991], but it is widely accepted that excessive grazing is detrimental to plant communities [*Milchunas and Lauenroth*, 1993]. Primary production in overgrazed grasslands can decrease if herbivory decreases plant growth capacity, vegetation density, community biomass, or if community composition changes [*Chapman and Lemaire*, 1993]. Additional effects of overgrazing include decreased species diversity, proliferation of unpalatable species, increased soil erosion, and degradation of soil quality [*Schlesinger et al.*, 1990; *Milchunas and Lauenroth*, 1993].

[3] Grasslands characteristically have high inherent soil organic matter (SOM) content averaging 331 Mg SOM ha^{-1} (to 1 m depth) [*Schlesinger*, 1977]. Soil organic matter is an important source of plant nutrients and can enhance production, increase soil aggregation, limit soil erosion, and increase cation exchange and water holding capacities [*Kononova*, 1966; *Allison*, 1973; *Tate*, 1987; *Miller and Donahue*, 1990], and is, therefore, a key regulator of grassland ecosystem processes. Soil organic matter, and soil carbon (C), are a function of the balance between inputs from primary production and outputs through decomposition. Soil C may decline if inputs decrease due to decreased net primary production as a result of overgrazing. Thus, grazing is an important human-controlled factor influencing grassland production which can deplete soil C [*Ojima et al.*, 1993].

[4] Changes in grassland management which reverse the process of declining productivity may lead to increased soil C. Thus, rehabilitation of areas degraded by historical overgrazing can potentially sequester atmospheric C. The purpose of this study was to quantify the capacity of historically overgrazed grassland soils to sequester atmospheric C with improved grazing management. Our objectives were to (1) review the literature to determine how overgrazing affects soil C, (2) assess global potential for C sequestration with

0886-6236/02/2001GB001661$12.00

cessation of overgrazing, (3) identify physiographic regions with the greatest C sequestration potential, and (4) delineate geographic zones likely to sequester substantial atmospheric C with limited investment.

2. Methods

[5] We compiled data from the literature to evaluate the influence of overgrazing on soil C. A literature search was conducted beginning with a variety of web-based agricultural and ecological bibliographic databases (Commonwealth Agricultural Bureaux abstracts [*CAB*, 1999], Web of Science, and Agricola) with keywords relating to rangeland, pasture, or grassland and SOM or soil C to identify articles that compare soil C in heavily grazed areas with soil C in moderately grazed areas. Data requirements included proximally located comparative research sites with limited climatic and edaphic variability, no secondary treatments that could confound the effects of grazing on soil C, and well documented grazing histories. Further, we only included studies that reported soil C as mass of C lost per unit area since only soil C data reported in this manner can be extrapolated spatially. Thirty-five data points were excluded because only soil C concentrations (i.e., percent C) were reported; 23 other studies evaluating grazing impacts on soil C were reviewed [see *Conant et al.*, 2001], but compared grazed areas with ungrazed areas and were, thus, not appropriate for this study.

[6] We assumed that soil C lost under heavy grazing could be regained with rehabilitation of overgrazed lands. Thus, the C sequestration potential of overgrazed soils was assumed to equal the amount of soil C lost due to overgrazing. We equate heavy grazing with overgrazing since heavy grazing implies grazing intensities greater than those recommended. For example, *Schuman et al.* [1999] define their heavy grazing treatment as 33% greater than Natural Resources Conservation Service recommendation for the region, resulting in removal of approximately 50% of aboveground annual production Consistent use at this rate could exceed sustainable stocking rates, which precludes adequate dry matter residue levels and may lead to erosion or loss of productive capacity [*Holechek et al.*, 1995]. Estimated C sequestration capacity would exceed actual sequestration capacity if overgrazing has resulted in significant erosion, substantial replacement of productive species, or complete loss of productive capacity.

[7] Grazing intensities were usually quantified using stocking rates reported in animal unit months ha^{-1} (AUM ha^{-1}), or some variation thereof. Since sustainable stocking rates vary with primary production, stocking rates are often not universally indicative of grazing intensity. Stocking rates are meaningful, however, when comparing grazing intensities at neighboring sites with similar potential primary production. Thus, we used stocking rates as indicators of grazing intensity, but stocking rates between sites were not compared.

[8] Studies examining the effects of grazing intensity on soil C were irregularly distributed. Therefore, based on data contained within these studies, we used regression analysis to derive a relationship between potential C sequestration and climatic variables to extrapolate results from these studies. Stepwise regression analyses were performed using *SAS* [1985] to develop a relationship between potential C sequestration and mean annual temperature (MAT), mean annual precipitation (MAP), potential evapotranspiration (PET), and the ratio of MAP to PET (P:E). Mean annual temperature and MAP were obtained from a $0.5° \times 0.5°$ grid cell climate map developed for the POTSDAM project [*Schimel et al.*, 1996]. Potential evapotranspiration was calculated using mean monthly temperatures, the annual heat index, and a latitudinal correction factor [*Thornthwaite*, 1948]. The resulting regression equation allowed extrapolation of potential C sequestration to all overgrazed grassland areas.

[9] Grassland areas were identified using the Data Information System global land cover (DISCover) data set compiled by the International Geosphere Biosphere Program [*Loveland and Belward*, 1997]. The data consist of registered and classified advanced very high resolution radiometer (AVHRR) data at 1 km resolution. Continental coverages were compiled from 10-day NDVI composite data from 1992–1993 and classified into global ecosystem categories. We regrouped these data into four generalized groups: grassland and permanent pasture, forest, cultivated land, and other land. These categories conform with the FAO broad land use classification [*Food and Agriculture Organization* (*FAO*), 1999] and continental estimates of grassland area were highly correlated with coinciding FAO estimates (r^2 = 0.98) and were within 5% of FAO estimates.

[10] The Global Assessment of Soil Degradation (GLASOD) database was used to define overgrazed areas. GLASOD is a compilation of regional estimates of soil degradation assembled into a global coverage by the International Soil Reference and Information Centre [*Oldeman et al.*, 1990; *Oldeman*, 1994]. It is not based on sampling, but on regional expert opinion, making the data broadly accurate, but less certain at any particular location. Of the five causes of soil degradation contained in the GLASOD database, we focused on overgrazing. The area of overgrazed land was calculated for each of the four GLASOD severity classes, light, moderate, strong, and extreme, by multiplying the midpoint of the degradation extent class by polygon area [*Oldeman*, 1994].

[11] The GLASOD and IGBP DISCover data sets were integrated to generate a map of overgrazed grassland area for each severity class on each continent. Carbon sequestration estimates based on the relationship between reviewed data and climatic variables were extrapolated globally using the global climate coverages described above. All data were then integrated using a GIS to produce a global estimate of potential for C sequestration in soils of overgrazed grasslands following cessation of overgrazing and restoration of moderate grazing intensity.

3. Results

[12] Our literature review identified 22 data points from twelve studies that reported soil C in heavily and moderately grazed grassland ecosystems (Table 1). Most studies (58%) and data points (82%) were located in North America

Table 1. Grassland System Type, Sample Depth, and Soil C Under Two Grazing Intensities From a Variety of Published Sources[a]

Grassland System	Soil C, tC ha^{-1} Heavy Grazing	Soil C, tC ha^{-1} Moderate Grazing	Depth, cm	Source
Subtropical savanna	66.5	85.2	20	*Abril and Bucher* [1999]
Upland pasture	35.7 (1.0)	40.1 (0.6)	6	*Bardgett et al.* [1993]
Subalpine grassland	29.4	47.5	8	*Carr and Turner* [1959]
Typical steppe	7.9	11.0	6	*Chuulun et al.* [1999]
Mixed-grass prairie	140 (4.7)	117 (1.6)	107	*Frank et al.* [1995]
Grass/legume pasture	18.2 (1.5[b])	17.6 (3[b])	20	*Franzluebbers et al.* [2000]
Mixed-grass prairie	56.9 (1.7)	56.6 (0.6)	30	*Manley et al.* [1995]
Mixed-grass prairie	51.2 (1.7)	56.6 (0.6)	30	*Manley et al.* [1995][c]
Mixed-grass prairie	58.1 (1.7)	56.6 (0.6)	30	*Manley et al.* [1995][d]
Parkland fescue	45.0 (4.4)	42.5 (1.5)	10	*Naeth et al.* [1991][e]
Parkland fescue	40.0 (4.4)	52.5 (1.5)	10	*Naeth et al.* [1991][f]
Foothills fescue	60.0 (4.8)	55.0 (1.6)	10	*Naeth et al.* [1991]
Foothills fescue	62.5 (2.4)	55.0 (1.6)	10	*Naeth et al.* [1991]
Mixed-grass prairie	101.3 (1.5)	91.9 (0.5)	90	*Schuman et al.* [1999]
Mixed-grass prairie	17.7 (0.6)	14.9 (0.5)	10	*Smoliak et al.* [1972]
Typical steppe	34.9 (1.0)	37.4 (0.2)	100	*Wang and Chen* [1998]
Short-grass prairie	13.8 (0.22)	19.23 (0.16)	3	*Wood and Blackburn* [1984][c]
Short-grass prairie	13.8 (0.22)	21.4 (0.15)	3	*Wood and Blackburn* [1984][d]
Short-grass prairie	13.8 (0.22)	16.27 (0.15)	3	*Wood and Blackburn* [1984]
Mid-grass prairie	13.6 (0.22)	23.5 (0.16)	3	*Wood and Blackburn* [1984][c]
Mid-grass prairie	13.6 (0.22)	21.5 (0.15)	3	*Wood and Blackburn* [1984][d]
Mid-grass prairie	13.6 (0.22)	17.2 (0.15)	3	*Wood and Blackburn* [1984]

[a] Grazing intensities are in parentheses (AUM ha^{-1}).
[b] Pastures were grazed to maintain various amounts of available forage (Mg ha^{-1}).
[c] Deferred rotation.
[d] Short-term heavy grazing (also called high-intensity, low-frequency grazing).
[e] June grazing.
[f] Autumn grazing.

(Figure 1). One study [*Schuman et al.*, 1999] reported results on the same plots as another study [*Manley et al.*, 1995], but for a different duration. No studies reexamined study plots after implementation of moderate grazing following overgrazing; rather, all studies used a paired-plot approach that compared proximal plots under different grazing intensities. Information about net primary productivity under moderate and heavy grazing intensities was not reported for any of the studies, though *Schuman et al.* [1999] found that total aboveground biomass increased with decreasing grazing intensity.

[13] Grazing intensity averaged 0.68 AUM ha^{-1} for moderately grazed and 1.73 AUM ha^{-1} for heavily grazed plots, with an average grazing intensity on heavily grazed

Figure 1. Global distribution of study sites included in literature review.

Table 2. Total Grassland, Overgrazed Grassland, and Percent of Grassland That is Overgrazed, by Continent

Continent	Grassland, 10^6 ha	Overgrazed Grassland, 10^6 ha	Percent Overgrazed
Africa	838.2	87.7	10.4
Australia/Pacific	437.1	49.1	11.2
Eurasia	1385.9	85.6	6.2
North America	353.7	14.0	4.0
South America	402.2	26.2	6.5
Total	3417.1	262.5	7.7

plots 129% higher than moderately grazed plots (Table 1). Grazing animals were either cattle or sheep. Soil sample depth ranged from 3 to 107 cm and treatment duration averaged 17 years, ranging from 2 to 21 years. All studies but two took place in the Northern Hemisphere [*Bardgett et al.*, 1993; *Abril and Bucher*, 1999]. Average latitude from the equator was 42.1° and all data were from temperate and subtropical regions. Precipitation ranged from 304 to 1700 mm (average = 670 mm) and mean annual temperature ranged from −0.2 to 16.5°C (average = 9.8°C).

[14] Over 260 Mha, or 7.7%, of the world's grasslands were classified as overgrazed at the time of the GLASOD survey (Table 2). Nearly one-third of overgrazed grasslands occurred in both Africa and Eurasia, though only 6.2 and 10.4% of these continents were overgrazed, respectively. The Australia/Pacific (11.2%) region had the highest proportion of grassland that was overgrazed while the proportion of North American grasslands that was overgrazed was lowest (4.0%).

[15] Nearly 90% of overgrazing world-wide was of light or moderate severity (Table 3). The vast majority of the overgrazing in the Australia/Pacific region was light while overgrazing in Africa, Eurasia, North America, and South America was mostly of light and moderate severity. Africa had the most strongly overgrazed lands, with 25.9 Mha. Worldwide, 1.4 Mha were extremely overgrazed, most located in Eurasia (0.8 Mha) and the rest in Africa (0.5 Mha).

[16] Overgrazed grasslands in North America were largely restricted to the western United States, central Mexico, and southern Central America (mostly Panama, Costa Rica, and Honduras; Figure 2). Strongly overgrazed grasslands in North America were located in the southwestern United States. Overgrazed Eurasian grasslands were distributed across all of Asia from Ukraine in the west to China in the east. The most severely overgrazed grasslands were located in Ukraine and southwestern Russia, but large contiguous areas of overgrazed grasslands occurred across much of western Asia. Overgrazing in the Australia/Pacific region was largely restricted to Australia where lightly overgrazed grasslands were widespread. African overgrazed grasslands were primarily located in a belt around 15° latitude and in Southern and Eastern Africa with the worst degradation occurring in Ethiopia and South Africa. In South America, overgrazed areas occurred in many regions including high mountain pastures in Peru, Brazilian and Columbian savannas, and Argentinian Patagonia.

[17] Based on the assumption that the annual C sequestration rate equals the difference in soil C between moderately and heavily grazed treatments divided by the duration of treatment, a statistical model was generated relating annual C sequestration to climatic variables. Mean annual precipitation was directly related to annual C sequestration, and linear regression explained 29% of the variation across all study sites ($P < 0.01$; Figure 3). Inclusion of other climatic variables did not significantly ($P < 0.15$) improve the model. Though three points occur in areas with more than 1200mm annual precipitation, removing these data points from the regression did not substantially change the slope (0.00152 from 0.00134), intercept (−0.62 from −0.488), or the r^2 value (0.31 from 0.29) of the relationship. Changes in soil C with conversion from heavy to moderate grazing ranged from a loss of 0.33 Mg C ha^{-1} yr^{-1} to sequestration of 1.83 Mg C ha^{-1} yr^{-1}. Continental average sequestration rates were 0.21, 0.09, 0.05, 0.16, and 0.69 Mg C ha^{-1} yr^{-1} for Africa, Australia/Pacific, Eurasia, North America, and South America, respectively. The overall average C sequestration rate was 0.18 Mg C ha^{-1} yr^{-1}.

[18] The highest rates of potential C sequestration occurred in the wettest grassland regions including the south-central United States, central and western Africa and Madagascar, parts of South America, and northern Australia (Figure 4). The regression model predicted losses of soil C in the driest parts of all continents (below 333 mm yr^{-1}). Most (93%) of potential C sequestration was found to be in regions with precipitation less than 1800 mm yr^{-1}. Estimated total C sequestration potential in regions with precipitation less than 1000 mm yr^{-1} was nearly equal to that in wetter regions with precipitation between 1000 and 1800 mm yr^{-1}.

[19] The spatial distribution of C sequestration potential in overgrazed grasslands followed the distribution of overgrazed grasslands: most (83%) C sequestration potential identified was located in areas that were lightly (13.3 Tg C yr^{-1}) or moderately (24.6 Tg C yr^{-1}) overgrazed while only a very small amount was located in strongly or extremely (7.4 Tg C yr^{-1}) overgrazed grasslands (Table 4). Africa, and, to a lesser degree, North America, were the major exceptions to this trend: 27 and 37% of C sequestration potential was found in strongly and severely overgrazed grasslands in Africa and North America, respectively. Together, Africa (37%) and South America (40%) were the continents with most of the global potential to sequester C in soil with cessation of overgrazing and implementation of moderate intensity grazing. Potential C sequestration estimates based on regression output should be discounted for the severely overgrazed regions since those regions have been degraded beyond recovery [*Oldeman*, 1994].

[20] Though most soil C sequestration potential occurred in wetter regions, significant potential also exists in drier regions (Table 5). Regions with P:E ratios less than one

Table 3. Portion (%) of Overgrazed Land Within Each Severity Class, by Continent

Continent	Light	Moderate	Strong	Extreme
Africa	34.6	35.2	29.6	0.6
Australia/Pacific	97.5	2.3	0.2	0.0
Eurasia	54.8	41.8	2.4	1.0
North America	14.5	73.4	12.1	0.0
South America	35.8	57.6	6.6	0.0
Total	52.0	35.5	12.0	0.5

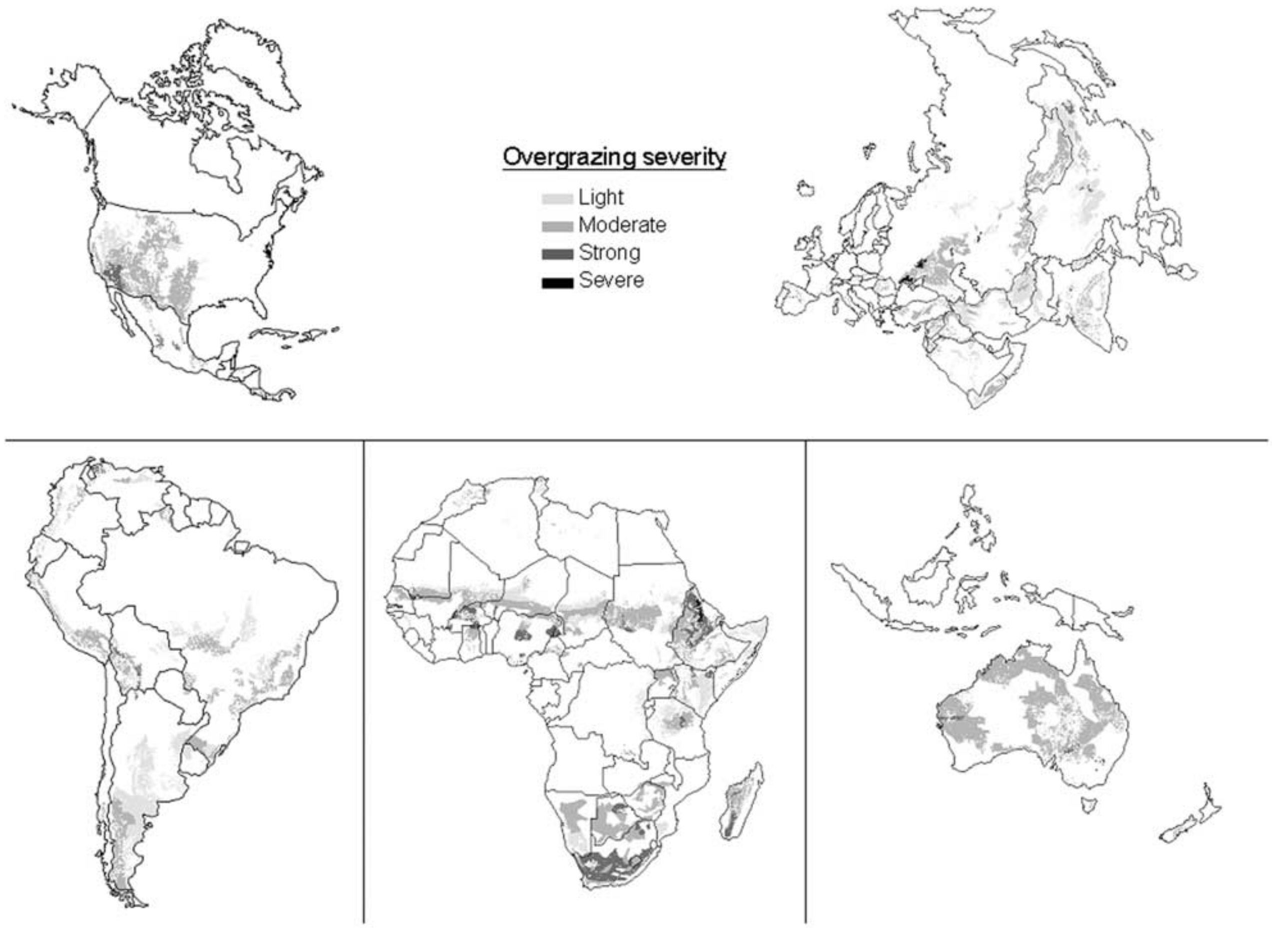

Figure 2. Global distribution of overgrazed grasslands for all four GLASOD degradation classes.

comprise more than 25% of the total C sequestration potential even though regression results suggest that substantial portions of these regions may lose soil C with implementation of decreased grazing intensity. Carbon sequestration potential is largely confined to temperate and tropical regions due, in part, to limited grassland area in boreal regions (12.7% of all grasslands). Equivalent P:E ratios in tropical and temperate regions equate to higher amounts of precipitation in tropical regions due to greater PET. Therefore, within any moisture class (Table 5) tropical regions had higher rates of potential C sequestration (per unit area) since MAP was greater.

4. Discussion

[21] Our results suggest that arresting overgrazing and implementing moderate grazing intensity can sequester substantial amounts of atmospheric C in grassland soils. Grasslands in wet, mesic, and dry temperate, tropical, and subtropical regions promise to sequester C with decreased grazing intensity on overgrazed grasslands. Carbon sequestration is likely on all continents, though Africa and South America exhibit the largest potential due to the significant amounts of overgrazed grassland in regions with more favorable climate.

[22] Carbon sequestration estimates were based on a limited number of data points that are unevenly distributed. We extrapolated C sequestration potential using a climatic driving variable since climate directly affects production and decomposition. The limited distribution of study sites, however, resulted in a regression relationship that represents C sequestration potential across a broader precipitation range than is represented by the study sites. Thus C sequestration potential in wet areas (MAP > 1800 mm) was determined by the relationship derived based on observations at the study sites which were, on the whole, drier. However, while this is an inherent weakness in the data set, a relatively small portion (7.2%) of estimated global C sequestration potential occurred in areas with MAP greater than 1800 mm. Additionally, most of the data used for this study were from samples collected from depths shallower than 30 cm. Of the studies sampled to more than 30 cm, soil C was greater under heavy grazing than under moderate grazing for five of eight data points, all of which were from grasslands containing blue grama. Shifts in species composition can lead to changes in root architecture that are not

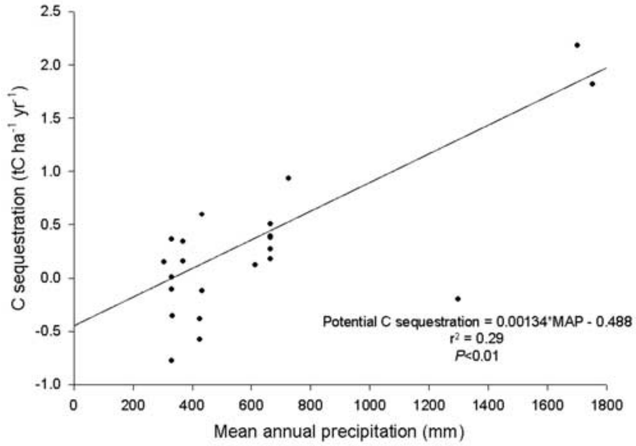

Figure 3. Relationship between annual change in soil C and mean annual precipitation including best fit linear regression line.

detectable without deep (>30 cm) sampling and are, thus, underrepresented in this data set.

[23] Of the studies that had increased soil organic matter with higher grazing intensities, half took place in areas with mixed C3/C4 grasslands containing the warm season grass blue grama (*Bouteloua gracilis*). Conversely, of the studies in areas with blue grama grass, half had an increase in soil C with increased grazing intensity. Since blue grama has a dense root structure, especially in the top 30 cm, *Frank et al.* [1995] concluded that blue grama produces soil C more efficiently than other prairie grasses and that increases in soil C with increased grazing were due to increased blue grama cover. Further, when measured, cover of blue grama tended to increase with grazing intensity [*Smoliak et al.*, 1972; *Frank et al.*, 1995; *Schuman et al.*, 1999]. Data from some of these studies suggests that heavily grazed plots may not be overgrazed to the extent that productive capacity is negatively impacted. *Kelly et al.* [1996] demonstrated that soil C is lower in interspaces than under grass bunches and is directly related to root biomass in shortgrass steppe. This suggests that soil C will increase when grazing leads to increased root biomass or vegetative cover, but will decrease beyond the point at which grazing negatively impacts root biomass. Only two studies reported information on soil C and belowground biomass and both found more soil C and more root biomass under the heavy grazing treatment [*Schuman et al.*, 1999; *Smoliak et al.*, 1972]. Thus, while grazing led to shifts in species composition

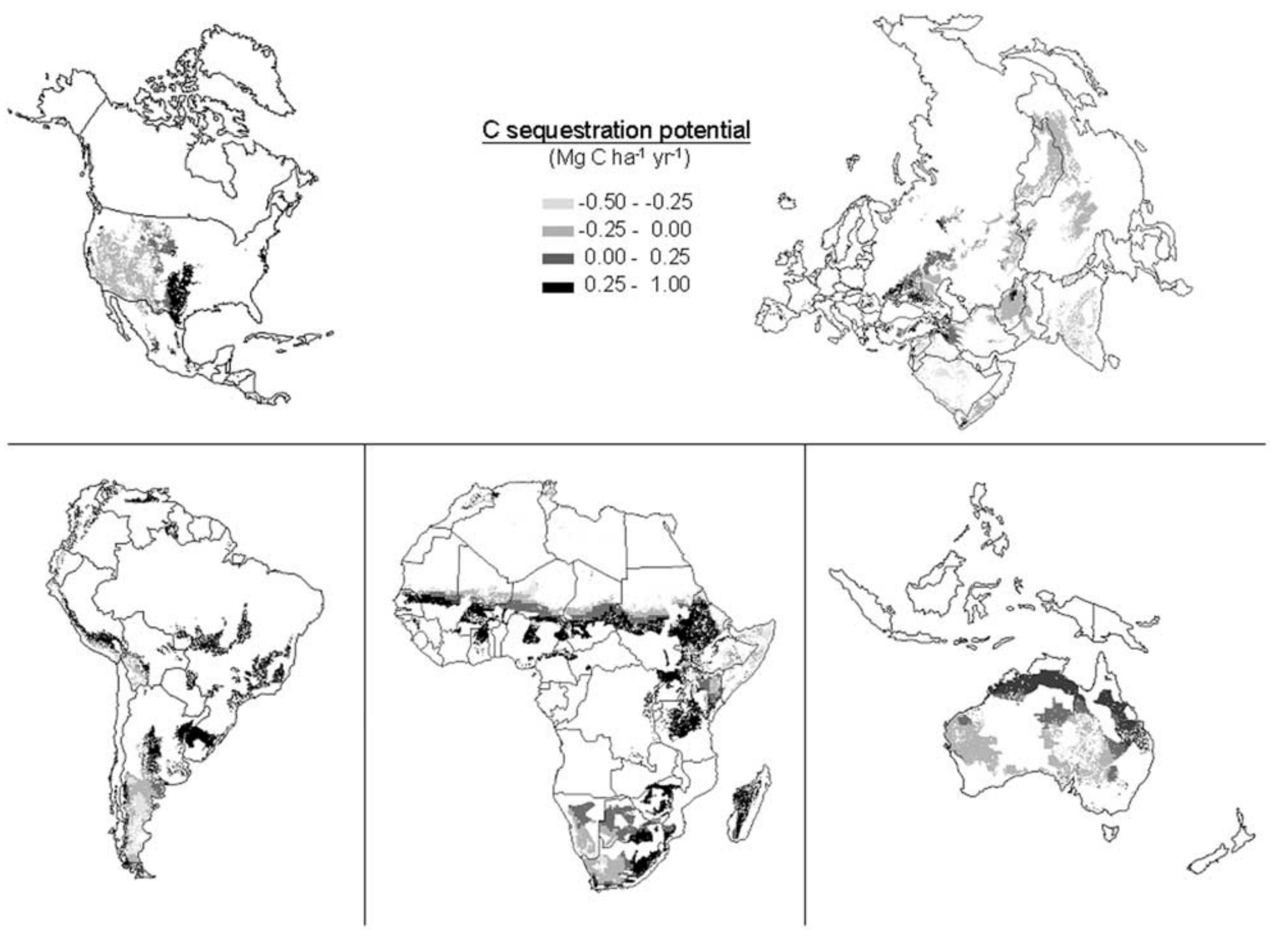

Figure 4. Potential annual C sequestration following cessation of overgrazing and implementation of moderate grazing intensities.

Table 4. Total Potential C Sequestration (Tg C yr^{-1}) Within Each Overgrazing Severity Class, by Continent

Continent	Light	Moderate	Strong	Extreme	Total
Africa	1.9	8.6	6.1	0.1	16.7
Australia/Pacific	4.5	−0.1	0.0		4.4
Eurasia	0.8	3.2	0.0	0.3	4.3
North America	0.0	1.6	0.6		2.2
South America	6.1	11.3	0.7		18.1
Total	13.3	24.6	7.4	0.4	45.7

favoring blue grama and aboveground biomass decreased, root biomass increased and soil C was greater under heavy grazing. It should be noted that the very heavily grazed site studied by *Naeth et al.* [1991] had less soil C than the heavily grazed site. Thus, it appears that grazing positively impacts belowground productivity, and soil C, at heavy, but not very heavy, stocking rates in blue grama-dominated grasslands.

[24] Nearly one third of the studies used to generate the relationship between changes in soil C following reduction of grazing and climate are from study sites containing blue grama grass. If increased soil C in response to increased grazing pressure in semiarid systems is unique to systems containing blue grama, then our results may underestimate C sequestration potential in areas without blue grama. Further, since heavy grazing often did not lead to decreased root, soil C, or cover, these heavy grazing treatments may not be overgrazed according to the GLASOD definition (i.e., productive capacity diminished). Removing those studies for which grazing led to increased cover or biomass and negative increased estimated global C sequestration potential by 28% (12.8 Tg C yr^{-1}) with the largest potential increases occurring in Africa (36%), Eurasia (23%), and North America (38%).

[25] Verification of the GLASOD database is difficult since (1) it is the only global-scale database of its kind, and (2) it is a soil degradation database. Most broad-scale grassland data sets focus on vegetation rather than the soil. For example, the Natural Resources Inventory [*U.S. Department of Agriculture*, 1994] in the United States is the broadest, most in-depth land use/management data set within the United States, but the best item for comparison with land area degraded from overgrazing from the GLASOD database is rangeland in poor condition (NRI - 23.2 Mha, GLASOD - 6.8 Mha). Correspondingly, other estimates of C sequestration potential in poorly managed rangeland systems in the United States (based on grazing of underutilized rangeland) are greater (8 Mg C yr^{-1} from *Schuman et al.* [2001] compared with our estimate of 2.2 Mg C yr^{-1} for all of North America) due to differences in area impacted by change in management. *Tothill and Gillies* [1992] developed a vegetation and soil degradation database for grazing lands of northern Australia. However, it is unclear whether all land classified as degraded by *Tothill and Gillies* [1992] is suffering from both soil and vegetation degradation, making data set intercomparison tenuous. *Tothill and Gillies* [1992] estimated that 43.3 Mha of grazing lands were deteriorated and 12.8 Mha degraded. The areal estimate for degraded land based on GLASOD and DISCover is similar (16.3 Mha). Furthermore, our estimate of C sequestration potential in northern Australia (5.5 Tg C yr^{-1}) is similar to that of *Tothill and Gillies* [1992] based on land use information and data gathered in desirably sustained and degraded lands in northern Australia (5.75 Tg C yr^{-1} assuming C sequestration continues for 25 years) [*Ash et al.*, 1996]. This intercomparison with independently derived data indicate that our estimates for potential C sequestration are reasonable.

[26] Decreasing grazing intensity on overgrazed grasslands can sequester substantial amounts of atmospheric C. Our estimate of potential C sequestration of 45.7 Tg C yr^{-1} through rehabilitation of overgrazed pastures is comparable to other estimates of CO_2 mitigation through changes in agricultural management. For example, *Cole et al.* [1997] estimated that 20–40 Tg C yr^{-1} could be sequestered globally with restoration of degraded lands and that a similar amount might be sequestered by permanent set aside of surplus agricultural land. It should be noted that estimates generated through this work include areas that will lose C when grazing intensity decreases for reasons described above. The average potential C sequestration for implementation of moderate grazing intensity, 0.18 Mg C ha^{-1} yr^{-1}, is lower than potential C sequestration rates observed for the Conservation Reserve Program (0.3–0.7 Mg C ha^{-1} yr^{-1}), the Grass Waterways program (0.3–0.7 Mg C ha^{-1} yr^{-1}), and adoption of no tillage (0.5–0.8 Mg C ha^{-1} yr^{-1}; *Lal et al.* [1998]). However, while average C sequestration rates per unit area are lower than those for other types of agroecosystem management improvement, soil degradation due to overgrazing is a widespread problem and the potential for C sequestration is substantial. Indeed, estimated C sequestration potential with improved pasture management comprises between 8–11% of IPCC estimates for C sequestration in agroecosystems [*Cole et al.*, 1996] and 9% of the estimate for C sequestration through sustainable management and changes in land use in grasslands and drylands under future climate and atmospheric regimes (540 Tg C yr^{-1}) [*Ojima et al.*, 1993].

[27] Of the four degradation classes in the GLASOD database, lightly degraded lands are most likely to benefit from cessation of overgrazing since 'restoration to full productivity is possible by modifications of the management' that are achievable by producers regardless of economic condition [*Oldeman*, 1994]. Restoration of moderately over-

Table 5. Distribution of Potential C Sequestration (Tg C yr^{-1}) in Grasslands in Different Latitudinal Zones and Moisture Regimes for Two Severities of Overgrazing[a]

Latitudinal Zone	Moisture Regime	Light/Moderately Overgrazed	Severely Overgrazed
Boreal	dry	0.4	0.1
Boreal	mesic	0.7	0.0
Boreal	wet	0.7	
Temperate	dry	1.0	0.2
Temperate	mesic	2.4	0.1
Temperate	wet	0.4	0.1
Tropical/Subtropical	dry	7.4	2.7
Tropical/Subtropical	mesic	20.6	3.9
Tropical/Subtropical	wet	4.3	0.7

[a] Moisture regime is based on P:E ratio (dry < 1, 1 < mesic < 2, 2 < wet) [*Holdridge*, 1967] and latitudinal zones were determined according to methods described by *Koppen* [1954].

grazed lands requires investments which are beyond the means of local farmers in developing countries while strongly degraded lands require major investments likely beyond the means of governments in developing countries [*Oldeman*, 1994]. Lightly degraded lands, which can potentially sequester 13.3 Tg C yr^{-1}, can presumably be restored with low costs and substantial C sequestration can be realized in moderately degraded lands (24.6 Tg C yr^{-1}), limited C sequestration (7.4 Tg C yr^{-1}) can be expected for the major investments required to rehabilitate strongly degraded grasslands. An additional consideration is that as severity of degradation increases, erosion is likely to increase. This aspect of overgrazing was not addressed in the review literature, but may decrease C sequestration potential while increasing costs associated with rehabilitation.

[28] Sequestering C in soil has been described as a win-win situation since CO_2 is removed from the atmosphere while increasing soil C results in many agronomic benefits including increased cation exchange capacity, increased soil fertility, increased water holding capacity, increased soil aggregation, and decreased erosion [*Kononova*, 1996; *Allison*, 1973; *Tate*, 1987; *Miller and Donahue*, 1990; *Lal et al.*, 1998]. Indeed, one study included in the review data concluded that management that increases soil organic matter in large particles resulted in increased water holding capacity [*Naeth et al.*, 1991]; water holding capacity is critical in drier regions where production is limited by soil moisture. Therefore, rehabilitating overgrazed grasslands can result in appreciable C sequestration and is likely to benefit production as well.

[29] **Acknowledgments.** This work was supported by a grant from the Ruminant Livestock Efficiency Program of the U.S. Environmental Protection Agency and by the U.S. Department of Agriculture. We appreciate the comments of two anonymous reviewers on an earlier version of this manuscript.

References

Abril, A., and E. H. Bucher, The effects of overgrazing on soil microbial community and fertility in the Chaco dry savannas of Argentina, *Appl. Soil Ecol.*, *12*, 159–167, 1999.

Allison, F. E., *Soil Organic Matter and Its Role in Crop Production*, 639 pp., Elsevier Sci., New York, 1973.

Ash, A. J., S. M. Howden, and J. G. McIvor, Improved rangeland management and its implications for carbon sequestration, paper presented at Fifth International Rangeland Congress, Salt Lake City, Utah, 1996.

Bardgett, R. D., J. C. Frankland, and J. B. Whittaker, The effects of agricultural practices on the soil biota of some upland grasslands, *Agric. Ecosyst. Environ.*, *45*, 25–45, 1993.

Carr, S. M., and J. S. Turner, The ecology of the Bogong high plains, II, Fencing experiments in grassland, *Aust. J. Bot.*, *7*, 34–83, 1959.

Chapman, D. F., and G. Lemaire, Morphogenic and structural determinants of plant regrowth after defoliation, in *Grasslands for Our World*, edited by M. J. Baker, pp. 55–64, SIR, Wellington, New Zealand, 1993.

Chuluun, T., L. L. Tieszen, and D. Ojima, Land use impact on C4 plant cover of temperate east Asian grasslands, in *NIES Workshop on Information Bases and Modeling for Land-use and Land-cover Changes Studies in East Asia*, edited by K. Otsubo, pp. 103–109, Cent. for Global Environ. Res., location, 1999.

Cole, C. V., et al., Agricultural options for mitigation of greenhouse gas emissions, in *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, edited by R. T. Watson et al., pp. 745–771, Cambridge Univ. Press, New York, 1996.

Cole, C. V., et al., Global estimates of potential mitigation of greenhouse gas emissions be agriculture, *Nut. Cycl. Agroecosyst.*, *49*, 221–228, 1997.

Commonwealth Agricultural Bureau, *Commonwealth Agricultural Bureaux Abstracts* [CD-ROM], London, 1999.

Conant, R. T., K. Paustian, and E. T. Elliott, Grassland management and conversion into grassland: Effects on soil carbon, *Ecol. Appl.*, *11*, 343–355, 2001.

Dyer, M. C., C. L. Turner, and T. R. Seastedt, Mowing and fertilization effects on productivity and spectral reflectance in *Bromus inermis* plots, *Ecol. Appl.*, *1*, 443–452, 1991.

Food and Agriculture Organization, *FAO STAT Statistical Database 1997*, Rome, 1999.

Frank, A. B., D. L. Tanaka, L. Hofmann, and R. F. Follett, Soil carbon and nitrogen of northern Great Plains grasslands as influenced by long-term grazing, *J. Range Manage.*, *48*, 470–474, 1995.

Franzluebbers, A. J., J. A. Stuedmann, H. H. Schomberg, and S. R. Wilkinson, Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA, *Soil Biol. Biochem.*, *32*, 469–478, 2000.

Georgaidis, N. J., R. W. Ruess, and S. J. McNaughton, Ecological conditions that determine when grazing stimulates grass production, *Oecologia*, *96*, 157–161, 1989.

Holdridge, L. R., Determination of world plant formations from simple climatic data, *Science*, *130*, 572, 1967.

Holechek, J. L., R. D. Peieper, and C. H. Herbel, *Range Management: Principles and Practices*, 526 pp., Prentice Hall, Old Tappan, N. J., 1995.

Kelly, R. H., I. C. Burke, and W. K. Lauenroth, Soil organic matter and nutrient availability responses to reduced plant inputs in shortgrass steppe, *Ecology*, *77*, 2516–2537, 1996.

Kononova, M. M., *Soil Organic Matter: Its Nature, Its Role in Soil Formation and in Soil Fertility*, 450 pp., Pergamon, New York, 1996.

Koppen, W., Classification of climates and world patterns, in *An Introduction to Climate*, edited by G. T. Trewartha, pp. 225–226, McGraw-Hill, New York, 1954.

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole, *The Potential of Cropland to Sequester Carbon and Mitigate the Greenhouse Effect, U. S.*, 128 pp., Ann Arbor, Chelsea, Mich., 1998.

Loveland, T. R., and A. S. Belward, The IGBP-DIS global 1 km land cover data set, DISCover: First results, *Int. J. Remote Sens.*, *18*, 3289–3295, 1997.

Manley, J. T., G. E. Schuman, J. D. Reeder, and R. H. Hart, Rangeland soil carbon and nitrogen responses to grazing, *J. Soil Water Conserv.*, *50*, 294–298, 1995.

McNaughton, S. J., Grazing as an optimization process: Grass-ungulate relationships in the Serengeti ecosystem, *Am. Nat.*, *113*, 691–703, 1979.

Milchunas, D. G., and W. K. Lauenroth, Quantitative effects of grazing on vegetation and soils over a global range of environments, *Ecol. Monogr.*, *63*, 327–366, 1993.

Miller, R. W., and R. L. Donahue, *Soils*, 768 pp., Prentice Hall, Old Tappan, N. J., 1990.

Naeth, M. A., A. W. Bailey, D. J. Pluth, D. S. Chanasyk, and R. T. Hardin, Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta, *J. Range Manage.*, *44*, 7–12, 1991.

Ojima, D. S., B. M. Dirks, E. P. Glenn, C. E. Owensby, and J. O. Scurlock, Assessment of C budget for grasslands and drylands of the world, *Water Air Soil Pollut.*, *70*, 95–109, 1993.

Oldeman, L. R., The global extent of soil degradation, in *Soil Resilience and Sustainable Land Use*, edited by D. J. Greenland and I. Szabolcs, pp. 99–118, CAB Int., New York, 1994.

Oldeman, L. R., R. T. Hakkeling, and W. G. Sombroek, *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*, Int. Soil Ref. and Inf. Cent., Wageningen, Netherlands, 1990.

SAS, *SAS User's Guide: Statistics Version 5*, SAS Inst., Cary, N. C., 1985.

Schimel, D. S., B. H. Braswell, R. McKeown, D. S. Ojima, W. J. Parton, and W. Pulliam, Climate and nitrogen controls on the geography and timescales of terrestrial biogeochemical cycling, *Global Biogeochem. Cycles*, *10*, 677–692, 1996.

Schlesinger, W. H., Carbon balance in terrestrial detritus, *Ann. Rev. Ecol. System.*, *8*, 51–81, 1977.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford, Biological feedbacks in global desertification, *Science*, *247*, 1043–1048, 1990.

Schuman, G. E., J. D. Reeder, J. T. Manley, R. H. Hart, and W. A. Manley, Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland, *Ecol. Appl.*, *9*, 65–71, 1999.

Schuman, G. E., J. E. Herrick, and H. H. Janzen, The dynamics of soil carbon in rangelands in *The Potential of Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*, edited by R. F. Follett, R. Lal, and J. M. Kimble, pp. 267–290, Lewis, Boca Raton, Fla., 2001.

Smoliak, S., J. F. Dormaar, and A. Johnston, Long-term grazing effects on Stipa-Bouteloua prairie soils, *J. Range Manage.*, *25*, 246–250, 1972.

Tate, R. L., *Soil Organic Matter: Biological and Ecological Effects*, 291 pp., John Wiley, New York, 1987.

Thornthwaite, C. W., An approach toward a rational classification of climate, *Geogr. Rev.*, *38*, 55–94, 1948.

Tothill, J. C., and C. Gillies, The pasture lands of northern Australia, in *Occasional Publication 5*, 93 pp., Trop. Grassland Soc. of Aust., Brisbane, Queensl., Australia, 1992.

U.S. Department of Agriculture, *Natural Resources Inventory Digital Data*, Natural Resour. Conserv. Serv., Washington, D. C., 1994.

Wang, Y., and Z. Chen, Distribution of soil organic carbon in the major grasslands of Xilinguole, Inner Mongolia, China, *Acta Phytoecol. Sinica*, *22*, 545–551, 1998.

Wood, K. M., and W. H. Blackburn, Vegetation and soil responses to cattle grazing systems in the Texas rolling plains, *J. Range Manage.*, *37*, 303–308, 1984.

R. T. Conant and K. Paustian, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, USA. (conant@nrel.colostate.edu; keithp@nrel.colostate.edu)